Introducing social acceptance into the design of CCS supply chains: a case study at a European level

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Abstract

The installation of infrastructures for carbon capture, transport, and storage to tackle the problem of CO_2 emissions from European power plants and carbon intensive industries, is of strategic importance to reach future greenhouse gases reduction targets. However, the public reaction to the deployment of these technologies is still uncertain, and opposition may result in either cancellations or delays. This article provides quantitative insights into how social acceptance affects the design of a European CO_2 infrastructure. A multi-objective mixed integer linear programming model is developed to optimise the design the entire supply chain, by simultaneously addressing the minimisation of the costs to install and operate the infrastructure and the maximisation of its community acceptance. The goal is to provide optimal supply chains in terms of costs, whilst considering the social behaviour of inhabitants towards the installation and operation of either CO_2 pipelines or injection wells. Results demonstrate how the methodology may be exploited to assess the response of local communities and identify design strategies aiming at a trade-off between economic objectives and social acceptance. Although the maximisation of social acceptance leads to a +34% increase in costs with respect to the economic optimum, it is shown that an intermediate solution between the two objectives (i.e., economics against acceptance) entails a just slight increase of +8% with respect to the cost of the best economic configuration.

Keywords: Carbon capture and storage, supply chain optimisation, mixed integer linear programming, social acceptance, risk perception.

List of symbols

Acronyms

CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation and storage
EOR	Enhanced oil recovery
EU	European Union
GHG	Greenhouse Gas
GWP	Global warming potential
IDV	Individualism vs. collectivism
IEA	International Energy Agency
IVR	Indulgence vs. restraint
LCA	Life cycle assessment
LTO	Long-term orientation
MAS	Masculinity vs. femininity
MILP	Mixed integer linear programming
NIMBY	Not-in-my-back-yard
OptG	Optimality gap
PDI	Power distance index
SC	Supply chain
SolT	Solution time
UAI	Uncertainty avoidance index

Sets

c	Country, c={list of European countries}
d	Cultural dimension, d={PDI, UAI, LTO, IDV, MAS, IVR}
g	Region, g={1, 2, …, 133, 134}
k	Capture technology, $k=\{post_{coal}^{comb}, post_{gas}^{comb}, oxy_{coal}^{fuel}, pre_{gas}^{comb}\}$
l	Transport mode, l={onshore, offshore}

Parameters

$benefit_c$	Benefit parameter in country c
$dim_{d,c}$	Hofstede's cultural dimension d in country c
Pop_g	Population in region g
$\overline{Pop}_{g,g'}$	Average population between region g and g'
$risk_g$	Risk parameter in region g within country c [(people)$^{-1}$·(t of CO_2)$^{-1}$]
$\overline{risk}_{g,g'}$	Average risk parameter between region g and g' [(people)$^{-1}$·(t of CO_2)$^{-1}$]
$W_d^{benefit}$	Weight of cultural dimension d for benefit calculation
W_d^{risk}	Weight of cultural dimension d for risk calculation

Variables

$H_{g,g'}$	Pipeline holdup between region *g* and *g'* [t of CO_2]
RP	Risk perception
RP^{seq}	Risk perception on sequestration stage
RP^{trans}	Risk perception on transport stage
S_g	Stored CO_2 in region *g* [t of CO_2]
TC	Total cost [€]
TCC	Capture cost [€]
TSC	Sequestration cost [€]
TTC	Transport cost [€]

1. Introduction

The XXI Conference of the Parties of the United Nations Climate Change Conference held in 2015 negotiated the Paris Agreement, aiming at limiting the raise in global temperature to well below 2°C compared to pre-industrial level. The 195 countries that signed the agreement, should substantially reduce the emission of anthropogenic greenhouse gases (GHGs) to limit the global temperature increase by 2050. Furthermore, the International Energy Agency (IEA) highlighted that the development and implementation of technologies for carbon capture and sequestration (CCS) might constitute an effective short-term solution, for contributing to the reduction of 20% of the GHGs emissions before 2050 (IEA, 2015). In fact, CCS is the only technology considered nowadays able to directly decarbonise major industrial facilities such as power generation, cement, petrochemical and steel industries, without necessitating a complete rethinking of the industrial sectors (IPCC, 2018). Several studies have demonstrated the good environmental performance that could be achieved through implementing CCS to conventional systems (e.g., fossil fuel-fed power plants) and in combination with renewable options. For instance, Zhu et al. (2015) assessed the CO_2 emissions reduction potential through CCS for the case of China, indicating that CCS should be developed along with other alternative options to achieve energy scenarios with low GHGs output. Pang et al. (2017) analysed the integration of CCS into biomass-based power plants in terms of emissions reduction and ecological performance, showing emerging trade-offs between these two objectives. Wang et al. (2017) proposed a GHG assessment of CCS processes applied to solar-assisted post combustion capture through a life cycle approach (LCA), demonstrating that a reduction of about 70% of emissions could be achieved. Moreover, a review by Cuéllar-Franca and Azapagic (2015) analysed LCA studies on CCS and found that the global warming potential (GWP) of fossil fuel-based power plants can be decreased by 63-82% by implementing CCS.

Having recognised the importance of CCS, the European Community allocated different research funds (for instance, Horizon 2020, NER 300, LIFE climate action) for the development of techniques that allow a reduction of GHGs and the determination of the techno-economic aspects in the different echelons of the CCS supply chain (SC) (European Commission, 2019). This research effort and further academic projects laid the foundations for several studies, proposed along the years, which provided a deep increase in the techno-economic knowledge of each single stage of the SC (Global CCS Institute, 2017). Besides, it emerged the necessity of investigating the design, cost and integration of the CCS stages for the different geographic contexts and applicative frameworks (Bui et al., 2018). In view of this combinatorial complexity, optimisation techniques and mixed integer linear programming (MILP) have been recognised as a powerful tool for the extraction of quantitative preliminary information for an early planning of large-scale networks (Beamon, 1998). MILP models represent a well-established technique in many industrial fields and scopes of application, and it is commonly employed to solve large combinatorial optimisation problems without excessively increasing the computational burden (Heuberger et al., 2018). Indeed, to reduce the computational effort and solution complexity, MILP models are the most practical and most commonly adopted option when tackling large-scale instances (Mula et al., 2010). The first application of mathematical programming to a proper SC optimisation framework can be retrieved in a study on enhanced oil recovery (EOR) by Turk et al. (1987). Since then, several contribution have been proposed for the optimisation of CCS systems (Li et al., 2019a). As reviewed by Tapia et al. (2018), different mathematical models have been published in the last decade to optimise CCS infrastructures for the geographic context of Europe (for instance, d'Amore and Bezzo, 2017) or the Unites States (Hasan et al, 2015). Santibanez-Gonzalez (2017) presented a CCS SC model for the Brazilian cement industry, including an assessment on the effects of introducing a carbon tax in the optimal design of the network. Other contributions included the possibility of utilisation of the CO_2 as an alternative to storage (i.e., carbon capture and utilisation - CCU). For instance, Han and Lee (2012) proposed a stochastic multi-period model for the eastern coast of Korea, while Kwak and Kim (2017) optimised a CCU SC for EOR. Other works took into account different sources of uncertainty within the modelling framework. For example, Nie et al. (2017) proposed a CCS optimisation for the United Kingdom under market prices uncertainty, Lee et al. (2019) utilised preference on risk to optimise a SC for North Korea, whereas d'Amore et al. (2019) maximised the resiliency of a European CCS SC towards uncertainty in geological storage capacities. Finally, other articles investigated through MILP techniques aspects related to societal risk (in terms of safety) on the transport infrastructure (d'Amore et al., 2018).

Despite great research and investment efforts, in 2018 only 48 CCS plants were in operation or under construction worldwide, whereas estimates indicate that around 3500 CCS plants should be active to achieve a carbon reduction target of at least 20% of globally emitted CO_2 (Global CCS Institute, 2017). The hesitation in deploying CCS is often driven by a negative perception of the technology by the public. For lack of social acceptance, different injection projects have experienced strong protests and opposition by the communities living in their vicinity: one of the most notorious examples is the commercial project promoted by Shell in Barendrecht, The Netherland, which was cancelled due to the firm public opposition. Similarly, the planning by Vattenfall Group of a storage site in Beeskow, Germany, was cancelled, too (Oltra et al., 2012).

Notwithstanding the undeniable benefits of having CCS in the portfolio of technologies to fight climate change, many criticisms have been raised on their technical viability, efficacy and safety. Apart from concerns on the utilisation and operation of CCS, the problem of its social acceptance and public support has been highlighted as of fundamental importance in the process of fostering a large-scale deployment (Ashworth et al., 2015). For instance, people might be concerned about the safety issues in terms of risk of hazards deriving from CCS operation thus, the possibility of CO_2 leakage endangering both communities, commodities, and environment in the vicinity of an infrastructure (Yang et al., 2016). In particular, risk perception is intended as a measure of how much worry or concern is perceived by the public as a consequence of the construction and operation of a CCS infrastructure. As a matter of fact, Schumann (2017) assessed the public perception of CO_2 pipelines construction by the general public in Germany, based also on risk perception. This contribution highlighted that citizens' perception is of fundamental importance in the planning of such infrastructures. Similarly, Ashworth et al. (2019) analysed the results of a survey to determine the different perception of CCS across Australia and China, demonstrating how strongly the level of knowledge affects the public support towards these technologies. Moreover, being CCS an ‘end-of-the-pipe’ solution, the public might see it as a ‘last resource’, to which the utilisation of other low carbon technologies should be preferred (e.g., solar, wind, geothermal) (L’Orange Seigo et al., 2014). Besides, the employment of CCS by fossil fuel industries could be interpreted as a way of prolonging their own existence rather than enabling a genuine energy transition. In view of this, different strategies for a stronger engagement of the public living close to a CCS infrastructure have been recently proposed. For example, by providing information on the environmental benefits of CCS, it is possible to stimulate its social acceptance and potentially avoid protests and opposition (Oltra et al., 2012; Ashworth et al., 2012). However, it would be helpful for investors and policy makers to be able to assess a priori the different levels of opposition of different communities and possibly to design a cost-effective CCS supply chain (SC) maximising social acceptance.

Some previous contributions aimed at investigating and tackling through tailored strategies the problem of social acceptance for different energy-related fields. Ervural et al. (2018) developed a multi-objective model for renewable energy planning, including a fuzzy social acceptance factor based on experts’ opinion. Accordingly, the acceptance of general public was not explicitly taken into account. Li et al. (2019b) proposed a model for promoting low emission vehicles in China, also including aspects of market acceptance, but again based on data retrieved from a limited sample of experts’ opinions. Acar et al. (2019) proposed a comprehensive study for investigating energy storage systems considering economic, environmental, social and technical aspects through a fuzzy-based methodology. However, their methodology did not provide any indications in terms of optimal design and planning from a systems perspective. Regarding the CCS framework, Small et al. (2019) modelled a Bayesian framework for establishing which technological and socioeconomic factors could more likely affect the implementation of CCS. Their methodology, again based on experts' judgement, was only aimed at determining the key drivers for acceptance, but did not provide any indications on how to implement such aspects within a comprehensive framework, e.g. SC optimisation. Arning et al. (2019) compared CCS and CCU in terms of public perception and acceptance for the case of Germany. From this study, it emerged that CO_2 disposal and utilisation may help decreasing the risk perception of transport and storage infrastructures. Nevertheless, their study was based on a survey that did not take into account individual sociocultural factors and public attitudes. Summing up, despite the existence in the literature of quantitative methodologies for the determination of social acceptance related to the installation and deployment of energy systems (less frequently, focussing on CCS or CCU), the possibility to employ the attitude of generic public explicitly as a decision variable for the optimal design of a large-scale infrastructure, was never taken into account. To our knowledge, this contribution aims at filling this gap by proposing a decision tool where both economic factors and social acceptance are implemented as design variables, to optimise the installation and deployment of a European CCS infrastructure and to provide indications on the design and cost of those SCs that are more likely to be accepted or rejected by local communities. The social acceptance model will be employed to determine which communities are more likely oppose to CCS within the framework of a comprehensive MILP multi-objective optimisation, i.e. aiming at the simultaneous minimisation of costs for installing and operating the SC, and at the maximisation of its social acceptance (Figure 1). The model will be capable at quantifying the additional cost (with respect to an acceptance risk-neutral SC) that would be needed to design a CCS SC in the context of Europe that minimises the risk of rejection from local communities. Assessment of costs and of the risk of protests and opposition could provide a critical insight into a European large-scale application for CCS and foster its implementation more firmly and effectively.

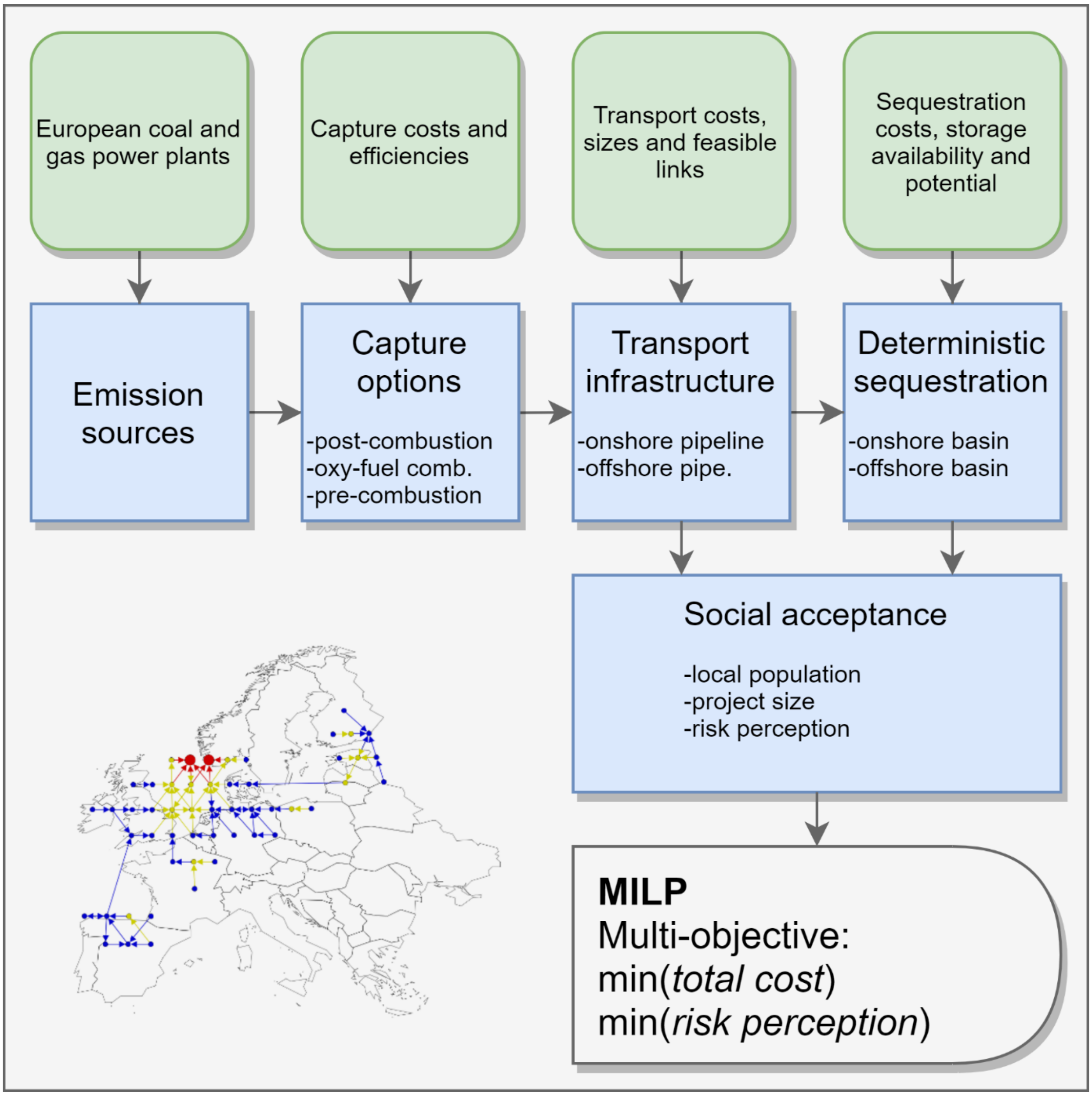


Figure 1. Basic operating principle of the CCS SC MILP optimisation framework.

2. Material and methods

2.1 Modelling social acceptance

Considering the wide range of industrial sectors and applications covered (e.g., energy systems, civil engineering, infrastructures), social acceptance-related studies have so far become of key importance for governments, industries and academics (Upham et al., 2015). Concepts like public opinion, perceptions, acceptance, attitude, behaviour, values and practise cannot be overlooked anymore, and social acceptance has come to be noticed as one of many aspects that may lead to the successful implementation of new developments or policies, especially in the energy field.

The energy sector is commonly considered as one of the key fields of research on social acceptance (Wolsink, 2018), and might constitute a fertile land for retrieving quantitative methodologies that may be applied to CCS modelling. For instance, Van der Horst and Toke (2010) proposed a study on acceptance of wind farms in the United Kingdom. Their model was based on a list of either approved or rejected wind farms between 1991 and 2006, and on a dataset concerning socio-economical information (e.g., education, health, demography, employment) obtained from inhabitants of rural areas. Similarly, Roddis et al. (2018) proposed a study on social acceptance focused on both wind and solar farms in the United Kingdom, by aim of a dataset of either approved or rejected facilities between 1990 and 2017, together with the description of both attitudinal and social arguments. This class of methods, however, requires both a dataset of quantitative parameters based on material or attitudinal/social arguments, and a list of previous accepted or rejected infrastructure applications, which in the case of CCS is practically unavailable, considering the early stage of implementation of this technology (Reiner, 2015; 2016).

Regarding studies specifically focussed on public perception of CCS, during the last decade researchers tried to understand the correlations between aspects such as acceptance, knowledge of the technology, trust in institutions, attitude, fairness, perceived cost, perceived benefit, and perceived risk (Karimi and Toikka, 2018). Oltra et al. (2012) and Ashworth et al. (2012) compared several case studies of CCS projects, indicating a series of factors that may influence public reaction towards CCS and its acceptance. However, none of these factors has been quantified in strict mathematical terms. Additionally, given the scarcity of active industrial applications of CCS, surveys and interviews cannot be always employed as sources of information on public perception, being often the respondents too few and endangered by a lack of impartiality (L'Orange Seigo et al., 2014). Other studies aimed at measuring the general public reactions in localities in the near vicinity of a proposed energy facility and, in some cases, a CCS system. Huijts et al. (2007) discussed the results from a survey on acceptance of CCS nearby a potential storage site. Groothuis et al. (2008) assessed the compensation level required to attain the acceptance of windmills in North Carolina. Subsequently, monetary compensation was indicated also as a potential help to foster also CCS implementation (ter Mors et al., 2012). These aspects were additionally revised and expanded by Terwel and ter Mors (2015) for the context of the Netherlands. Terwel et al. (2009) applied a methodology for evaluating perceived benefit, risk, and trust, in the context of CCS. Dütschke (2011) analysed the main drivers for local public acceptance for two case studies located in Germany. The public response in the vicinity of a planned sequestration basin was investigated by Oltra et al. (2012) for different case studies. Then, the consequences of informing public opinions about CCS were investigated by ter

Mors et al. (2013). From this contribution, it emerged that information-choice questionnaires delivered higher-quality opinions than focus groups. Overall, from these studies, it emerged a general support for CCS but an opposition to local projects, which is addressed in the literature as the "not-in-my-back-yard" (NIMBY) effect (Braun, 2017). Nonetheless, this class of studies alone cannot be used to set up a quantitative methodology supporting CCS SC optimisation.

On the other hand, models based on the concepts of risk and benefit perception can be considered of significant importance for the optimisation problem addressed by this contribution. Pietzner et al. (2011) uncovered how different countries have a different public perception of CCS technologies. Wallquist et al. (2012) employed risk and benefit perception as proxies for evaluating the acceptance of the CCS echelons. Following these studies, Karimi et al. (2016) developed a methodology showing how cross-cultural characteristics of countries play a role in risk and benefit perception of a technology, concluding that some nations are more likely to accept a new technology compared to others. This study was subsequently updated by Karimi and Toikka (2018), which proposed a model for investigating the socio-cultural orientation/attitudes of countries and their influences in the reaction (and acceptance) of people towards CCS technologies, to understand if a countrywide cultural behaviour determines how people perceive CCS. The model was built by taking into account:

- A survey conducted by the EU commission on the knowledge of CCS technology in 12 European countries, specifically countries where CCS projects were already started or planned (Eurobarometer, 2011). This study entails a total of 13901 respondents (with a minimum countrywide sample of 1000 respondents) and has been conducted in Bulgaria, Czech Republic, Finland, France, Germany, Greece, Italy, Netherlands, Poland, Romania, Spain and United Kingdom.
- A study by Hofstede et al. (2010), which aimed at characterising the socio-attitudinal characteristic (or cultural dimensions) of each country by aim of different factors. These quantities describe the general attitude of a citizen of a country in relative terms with respect to others and each dimension indicates how people living in that country tend to behave or approach certain issues. In particular, six main dimensions emerged as highly influential from that study: power distance index (PDI), individualism vs. collectivism (IDV), masculinity vs. femininity (MAS), uncertainty avoidance index (UAI), long-term orientation (LTO) and indulgence vs. restraint (IVR) (Hofstede et al., 2010).

In their work, Karimi and Toikka (2018) analysed the results from the Eurobarometer survey (Eurobarometer, 2011) and extended them to further countries according to the methodology proposed by Hofstede et al. (2010) (and other articles on social acceptance), by describing the public perception towards CCS through risk perception ($risk_g$) and benefit perception ($benefit_g$) parameters in region g belonging to country c:

$$risk_g = \sum_d W_d^{risk} \cdot dim_{d,g} \qquad \forall g \in c \qquad (1)$$

$$benefit_g = \sum_d W_d^{benefit} \cdot dim_{d,g} \qquad \forall g \in c \qquad (2)$$

where $dim_{d,g}$ (reported in Table S.4 in the supplementary material) represents the countrywide values of Hofstede's cultural dimensions (Hofstede et al., 2010) d={PDI, UAI, LTO, IDV, MAS, IVR} and assumes the same value in every region g belonging to the same country c, while the parameters W_d^{risk} and $W_d^{benefit}$ (reported in Table S.5 in the supplementary material) are the weights (Karimi and Toikka, 2018) of cultural dimension d for the calculation of either $risk_g$ or $benefit_g$. Thanks to its quantitative approach, the method proposed by Karimi and Toikka (2018) can be incorporated within a CCS SC optimisation framework, with the aim of designing optimal large-scale SCs in terms of both minimum costs and maximum acceptance from inhabitants. The idea was implemented in this work, under the following assumptions:

- it is here chosen to exclude benefits from the formulation of social acceptance, since these are related to a rather generic perception of the large-scale mitigation effect of CCS on climate change and cannot be related to specific facilities, as required in a design problem. Conversely, the size of the planned/installed infrastructure and the number of inhabitants clearly affect social acceptance in terms of risk perception, since larger projects combined with high population densities are likely to generate stronger response by the public and a higher opposition may be expected (Braun, 2017).
- it is here chosen to exclude the capture stage from those infrastructures generating acceptance-related issues. In fact, the addition of a capture system to an already existing fossil fuel-based facility does not directly concern the public living in the vicinity of the plant, and therefore it is here assumed that the capture stage does not generate any acceptance-related issues. On the other hand, pipelines and sequestration basins may generate a strong social response as the infrastructure may be placed in areas in close contact with the public.

2.2 Modelling European CCS SCs

The model will provide a MILP strategic optimisation of a European CCS infrastructure (in terms of selection, positioning, and operation of capture and sequestration nodes, and transport routes), whilst considering the maximisation of social acceptance from the public inhabiting nearby the infrastructure. The spatial framework is geographically described through a grid of 134 squared cells g={1, 2, …, 133, 134}, whose size ranges from 123 km to 224 km (taken from d'Amore and Bezzo, 2017). This discretisation includes the European continent, few regions of North Africa and some offshore regions in the North Sea, where offshore sequestration basins are located and may be exploited (along with onshore storage options). Data and location of emission sources of CO_2 are obtained from the Emission Database for Global Atmospheric Research (EDGAR) published by Joint Research Centre (JRC, 2016). In particular, only large stationary emission sources (i.e., emitting more than 10^6 t of CO_2/year, corresponding to 37% of overall European CO_2 emissions) are considered, according to the indications provided by d'Amore and Bezzo (2017). These emissions can be captured according to a set of technologies $k=\{post_{coal}^{comb}, post_{gas}^{comb}, oxy_{coal}^{fuel}, pre_{gas}^{comb}\}$ thus, including post-combustion from either coal or gas power plants, oxy-fuel combustion applied to coal plants, and pre-combustion capture applied to gas plants (d'Amore and Bezzo, 2017). In particular, the data provided by d'Amore and Bezzo (2017) (as retrieved from IPCC (2005) and Rubin et al. (2015)) were used for the techno-economic characterisation of capture options k in terms of unitary capture costs, capture efficiencies, and matching with CO_2 sources. CO_2 flowrates can be transported from region g to region g' by mean of either onshore or offshore pipelines l={*onshore*, *offshore*}, towards sequestration in geological basins. Data on the location, capacity and characterisation of the most promising formations for CO_2 storage (i.e., deep saline aquifers, hydrocarbon and coal fields) is obtained from the EU GeoCapacity Project (EU GeoCapacity Project, 2009).

The design and operation of the resulting CCS infrastructure will generate a public response which is proportional to the risk perception, and will depend on the project size, on the population inhabiting within the region, and on the differential behaviour of countries. Overall, this contribution will optimise a European CCS SC through a multi-echelon, time-static, spatially-explicit, multi-objective, MILP model, aiming at the simultaneous minimisation of total costs (*TC* [€]) and risk perception (*RP*):

$$\begin{cases} objective = \min(TC, RP) \\ s.t. \\ capture\ problem \\ transport\ problem \\ sequestration\ problem \\ social\ acceptance\ problem \end{cases} \tag{3}$$

In particular, the modelling framework includes the capture, transport, sequestration, and social acceptance problems. The value of *TC* of Eq.(3) is given by the sum of the overall installation and operation costs deriving from the capture (*TCC* [€]), transport (*TTC* [€]), and sequestration (*TSC* [€]) stages, while *RP* of Eq.(3) is obtained according to the contributions of both transport (RP^{trans}) and sequestration (RP^{seq}) infrastructures in terms of generated risk perception:

$$TC = TCC + TTC + TSC \tag{4}$$

$$RP = RP^{trans} + RP^{seq} \tag{5}$$

On the one hand, for Eq.(4), *TCC* is calculated according to the optimal quantity of CO_2 captured in region *g* through technology *k*, *TTC* depends on the CO_2 mass balance for transport mode *l* employed between region *g* and *g'*, while *TSC* is evaluated on the basis of the optimal quantity of CO_2 that is sequestered in region *g*. Details on the calculation of cost components *TCC*, *TTC*, and *TSC* are fully reported in the supplementary material. The economic model of Eq.(4) determines the optimal selection, planning, positioning, and scale of the capture, transport, and sequestration infrastructure. On the other hand, the public acceptance model of Eq.(5) evaluates the public response towards the transport and storage stages, which is calculated on the basis of the size of the CCS project, of the population inhabiting within the region, and of the differential behaviour of countries in terms of risk perception. Risk perception variables RP^{trans} and RP^{seq} are set to be proportional to the population Pop_g [people] (reported in Table S.1 in the supplementary material) inhabiting in region *g* (or the average population $\overline{Pop}_{g,g'}$ [people] between region *g* and *g'*), to the size of CCS project in region *g* (described through either pipeline holdup $H_{g,g'}$ [t of CO_2], or stored quantity S_g [t of CO_2]), and to the risk perception parameter $risk_g$ [(people)$^{-1}$·(t of CO2)$^{-1}$] (reported in Table S.2 in the supplementary material) determined through Eq.(1) for every region *g* within country *c* (or the average risk parameter $\overline{risk}_{g,g'}$ [(people)$^{-1}$·(t of CO2)$^{-1}$] between region *g* and *g'*) (further details on the calculation of $risk_g$ are reported in the supplementary material):

$$RP^{trans} = \sum_{g,g'} H_{g,g'} \cdot \overline{Pop}_{g,g'} \cdot \overline{risk}_{g,g'} \quad (6)$$

$$RP^{seq} = \sum_{g} S_g \cdot Pop_g \cdot risk_g \quad (7)$$

Depending on the choice of optimising either costs, or risk perception, or a combination of both, the MILP model will minimise the corresponding objective function, and thus determine the optimal CCS SC configuration that allows reaching the chosen target. When pursuing an economic objective, the resulting SC will be arranged in such a way as to minimise the costs to install and operate the various CCS stages (i.e., capture, transport, and geological sequestration). When aiming at optimising the social acceptance, the SC will be planned and operated in those regions that allow keeping risk perception on transport and sequestration at minimum levels. Otherwise, trade-off configurations will be obtained for combinations of the two conflicting objectives (i.e., economics against acceptance). Overall, the model is designed as follows. Given the following inputs:

- geographical distribution of CO_2 emission clusters from large stationary sources;
- geographical distribution of CO_2 sequestration basins;
- spatial features of European territories;
- minimum CO_2 quantity to be captured in Europe;
- techno-economic parameters describing CO_2 capture options;
- techno-economic parameters describing possible transport logistics;
- techno-economic parameters describing CO_2 storage sites and injection wells;
- spatial quantification of inhabitants in the model regions;
- differential behaviour of countries in terms of risk perception.

The objective is to optimise the economic (i.e., *TC* minimisation) and the community acceptance (i.e., *RP* minimisation) performances of the resulting CCS SC. Accordingly, the model will provide as an output:

- geographic location, scale, and selection of CO_2 capture sites;
- geographic location, scale, and selection of CO_2 sequestration basins;
- definition and scale of transport infrastructure;
- exploitation of the European potential for CCS;
- economic performance of the CCS SC;
- risk perception performance of the transport infrastructure;
- risk perception performance of the injection system;

- social performance of the CCS SC in terms of risk perception.

2.3 Case study

Following the indications provided by the European Commission (Shogenova et al., 2014), the minimum European carbon reduction target α was set equal to 50% of European emissions (i.e., the model aims at capturing and permanently sequestering 50% of the total European emissions from large stationary sources). Three case studies will be here investigated according to the multi-objective solution of the optimisation:

- Scenario A (Figure 2, point A), entailing the economic optimisation of the CCS SC in terms of *TC* minimisation;
- Scenario B (Figure 2, point B), entailing the social acceptance optimisation of the CCS SC in terms of *RP* minimisation;
- Scenario C (Figure 2, point C), entailing an intermediate situation between the two conflicting objectives, corresponding to a trade-off SC that manages to keep *RP* low without penalising excessively the CCS SC in terms of *TC*.

The model response to different values of the carbon reduction target is discussed in the supplementary material.

3. Results

The model was implemented in the GAMS software (www.gams.com) and optimised through CPLEX solver on a quad core 2.3 GHz computer (32 GB RAM). The multi-objective optimisation was performed by aim of the ε-constrain method (Laumanns et al., 2006), which allows to optimise a bi-objective problem under a Pareto-based criterium, i.e. a situation in which an improvement in the solution of one first objective equals necessarily to worsening the solution of the secondary objective. Results clearly show the conflict between costs and risk perception (Figure 2), as those SC configurations positively affecting economics (i.e., lower total cost *TC*) exhibit a poor performance in terms of social acceptance (i.e., higher risk perception *RP*).

Table 1. Scenarios A-B-C: results from the bi-objective optimisation in terms of total cost *TC* [B€ or €/t of sequestered CO_2], risk perception *RP*, optimality gap *OptG* [%], and solution time *SolT* [s].

Scenario	α [%]	*TC* [B€]	[€/t]	*RP*	*OptG* [%]	*SolT* [s]
A	50	462.4	38.15	27204.1	1.6	<60
B	50	620.7	50.88	6.3	6.6	4969
C	50	499.8	41.25	2752.2	5.2	14579

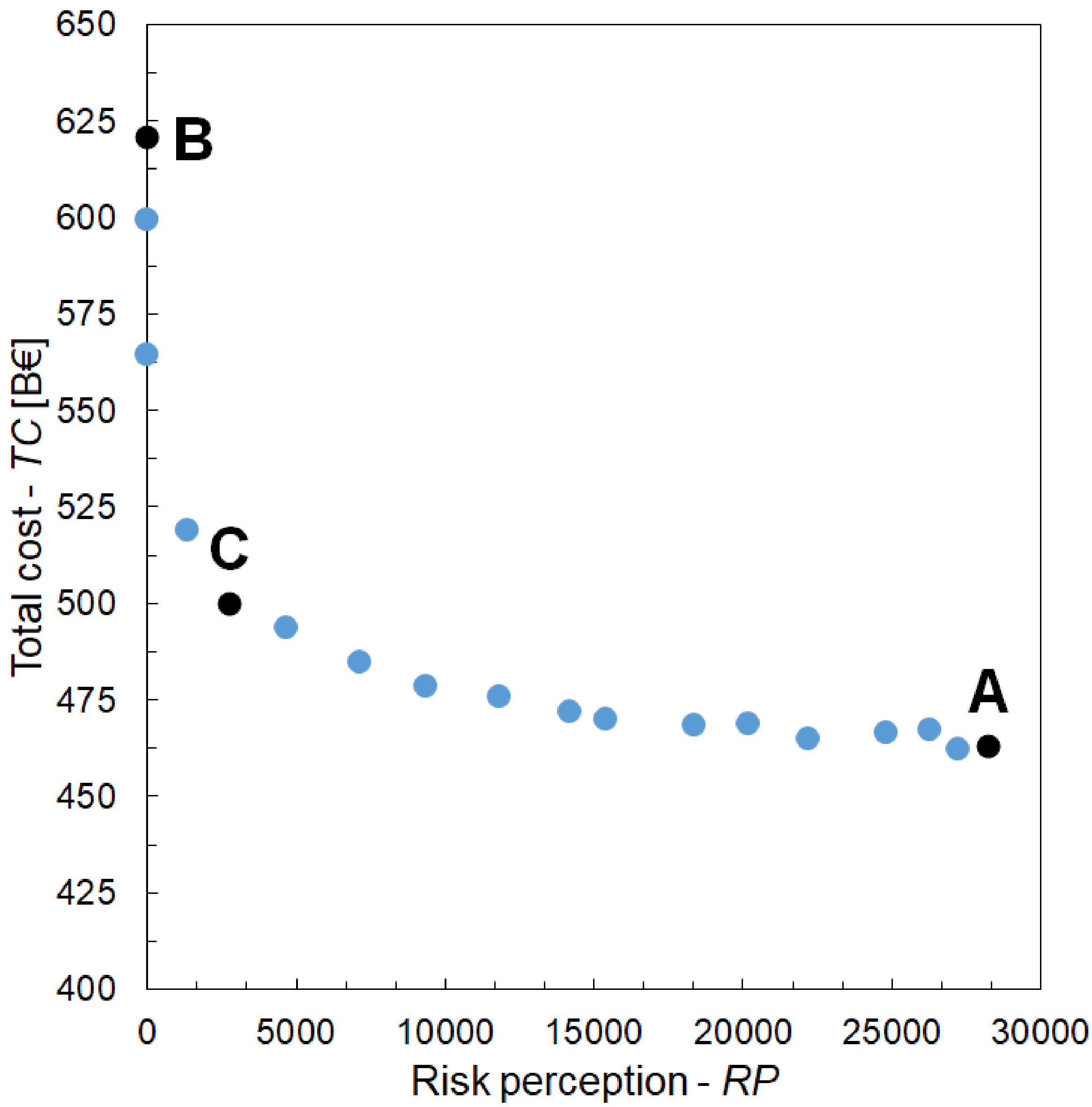


Figure 2. Pareto curve under bi-objective optimisation: the tree Scenarios are indicated.

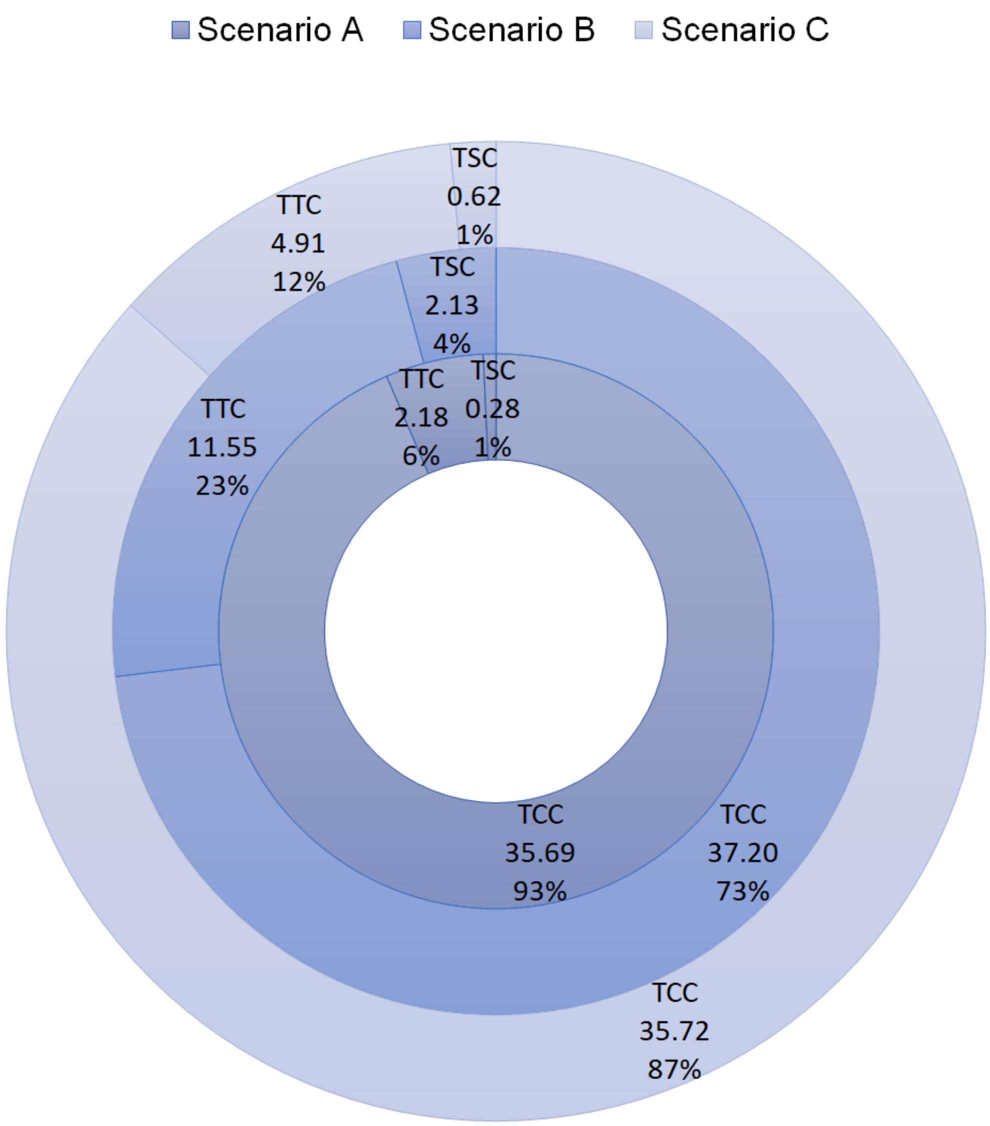
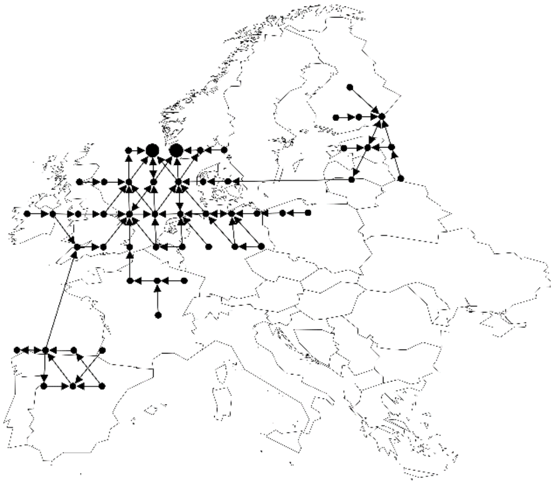


Figure 3. Scenarios A-B-C: results from the bi-objective optimisation in terms capture *TCC* [€/t of sequestered CO_2, and %], transport *TTC* [€/t of sequestered CO_2, and %], and sequestration *TSC* [€/t of sequestered CO_2, and %] costs contribution to overall investment *TC*.

(a)

(b)



(c)

Figure 4. Scenarios A, B, and C: SC configurations.

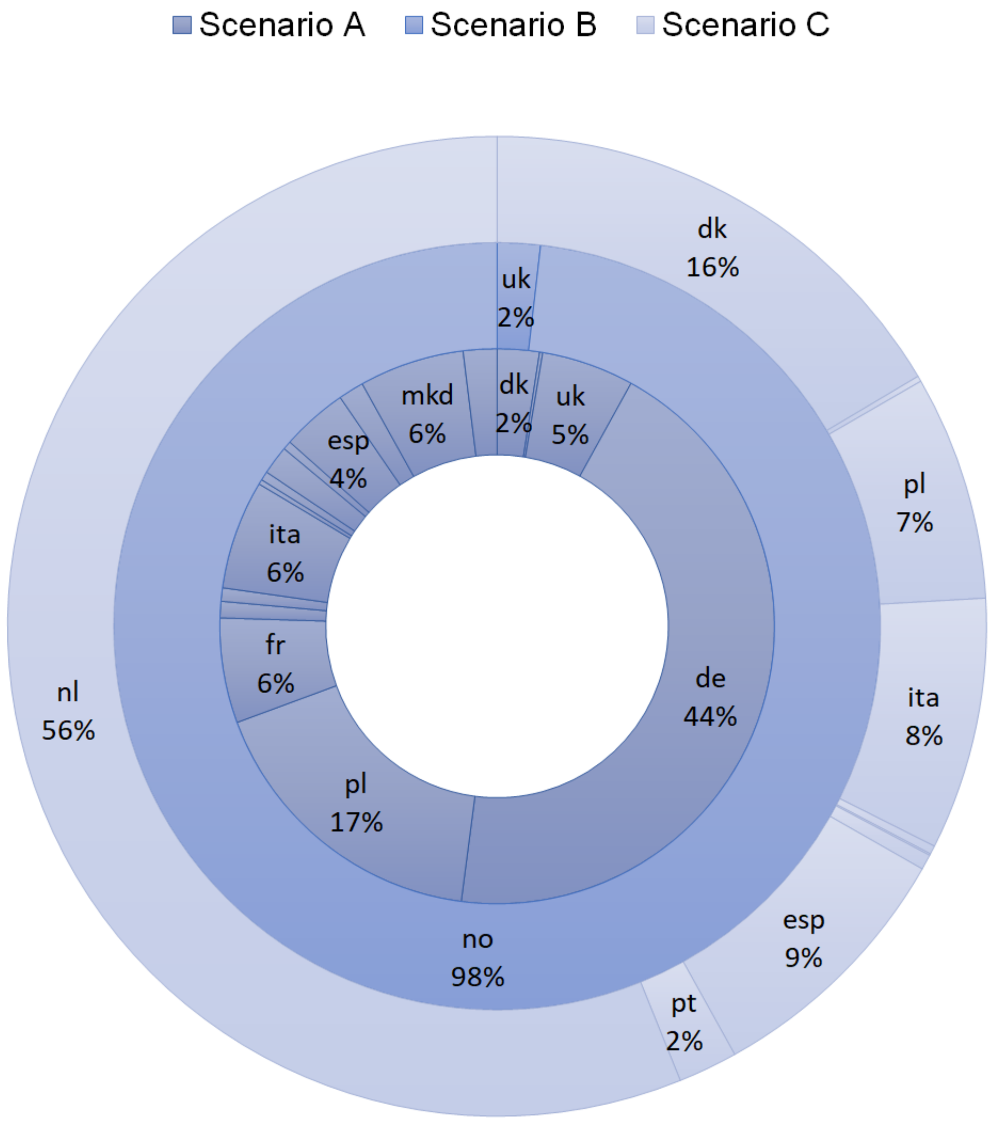


Figure 5. Main contributors to sequestration as results from optimal CCS SC optimisations for Scenarios A, B, and C. dk=Denmark, pl=Poland, ita=Italy, esp=Spain, pt=Portugal, nl=Netherlands, uk=United Kingdom, no=Norway, de=Germany, fr=France, mkd=Macedonia.

The European CCS system resulting under Scenario A entails (Table 1) a total cost *TC* to install and operate the SC of 462.4 B€ (billion Euros) (i.e., 38.18 €/t of sequestered CO_2), of which *TCC* for capture is 432.3 B€ (i.e., 35.69 €/t of sequestered CO_2), *TTC* for transport is 26.4 B€ (i.e., 2.18 €/t of sequestered CO_2), and *TSC* for sequestration is 0.3 B€ (i.e., 0.28 €/t of sequestered CO_2) (Figure 3). Furthermore, the optimal solution of the best economic SC entails the overall risk perception *RP* is equal to 27204, and constituted by a negligible transport risk perception RP^{trans} of about 1, opposed to a very large sequestration risk perception RP^{seq} of 27203. The resulting SC configuration (Figure 4a) is mainly developed within the mainland to minimise both transport and sequestration costs by avoiding offshore logistics and injection points, which generates noticeable values of risk perception as an obvious shortcoming. Moreover, risk perception generated by sequestration is much larger than that generated by the transport infrastructure. This difference can be explained considering the fact that the quantity of CO_2 that may be planned to be stored in geological basins can be up to the order of magnitude of 10^9 t of CO_2, whereas pipelines are designed to transport a maximum flowrate of 30 Mt of CO_2 on a yearly basis. Therefore, considering a CCS project in a region *g* with a certain population, RP^{trans} and RP^{seq} are calculated on the basis of pipelines holdups and stored quantities, and as a consequence RP^{trans} is likely to be quantitatively smaller than RP^{seq}.

The situation is completely different under Scenario B in terms of both economic result, community acceptance, and SC configuration. In fact, Scenario B exhibits (Table 1) a total cost *TC* of 620.7 B€ (i.e., 50.88 €/t of sequestered CO_2), i.e. +34% with respect to that of Scenario A. In particular, Scenario B entails a remarkable increase in transport *TTC* (equal to 140.9 B€, or 11.55 €/t of sequestered CO_2, i.e. +434%) and sequestration *TSC* (equal to 25.9 B€, or 2.13 €/t of sequestered CO_2, i.e. +853%) costs with respect to the best economic configuration obtained from Scenario A (Figure 3). These additional expenditures are needed to keep the levels of risk perception to minimum levels and to obtain the best SC in terms of social acceptance: RP^{trans} is almost null and RP^{seq} is reduced to zero. The increase in *TTC* and *TSC* costs with respect to Scenario A is explained considering the SC generated from Scenario B (Figure 4b): offshore sequestration in the North Sea is preferred to the (cheaper) onshore option (Figure 5). Regarding the positioning of capture facilities, CO_2 is captured in regions that are as close as possible to offshore basins to minimise the length of the pipelines and, accordingly, RP^{trans} as well.

As expected, Scenario C depicts an intermediate situation between the two extreme SC configurations represented by the solutions of Scenario A and Scenario B. In fact, Scenario C exhibits (Table 1) a total cost *TC* of 499.8 B€ (i.e., 41.25 €/t of sequestered CO_2, +8% and –189% with respect to Scenario A and Scenario B, respectively), constituted by a capture cost *TCC* of 432.9 B€ (i.e., 35.72 €/t of sequestered CO_2), a transport cost *TTC* of 59.6 B€ (i.e., 4.91 €/t of sequestered CO_2), and a sequestration cost *TSC* of 7.5 B€ (i.e., 0.62 €/t of sequestered CO_2) (Figure 3). The slight increase in *TC* with respect to Scenario A is needed to obtain an acceptable infrastructure in terms of risk perception *RP*, the latter equal to 2752 and significantly reduced (-899%) with respect to the optimal economic SC obtained for Scenario A. Unlike Scenario B (Figure 4b), in Scenario C (Figure 4c) offshore sequestration is only performed on basins nearby the United Kingdom (i.e., fairly close to the mainland), to limit the additional costs deriving from further transportation towards the North Sea. Concerning onshore sequestration, the most exploited basins for CO_2 storage are located nearby the Netherlands, Denmark, Spain, Italy, and Portugal (Figure 5). Just minor quantities are stored in locations within countries with high carbon intensity and high risk perception, e.g. Germany and Poland, at the cost of allowing some decrease in public acceptance with respect to Scenario B, while keeping infrastructural costs not too high with respect to Scenario A.

4. Discussion and limitations of the study

Different SC configurations emerged from the multi-objective optimisation of the system, depending on the choice of minimising either costs (Scenario A) or public risk perception (Scenario B), or a combination of both (Scenario C). The economic optimisation (Scenario A) confirms the results from previous studies in terms of both SC configuration and range of costs, and suggests sequestering the CO_2 in the same region where it is captured, in order to minimise the transport costs (Figure 5) (d'Amore and Bezzo, 2017). The resulting SC is constituted by an infrastructure, which is rather uniformly spread across Europe. The best configuration in terms of public acceptance (Scenario B) suggests sequestering all the CO_2 in the North Sea (Figure 5) to exploit basins that are located in regions with no population (thus, generating very low risk perception). Nevertheless, the resulting SC is too complex and expensive, and unlikely to be practically implemented. Conversely, the intermediate solution (Scenario C) represents a trade-off between economics and public acceptance, and could be employed to characterise the additional costs (+8% with respect to an acceptance risk-neutral SC) deriving from the design of a European CCS SC that takes into account, along with the economic decision variables, the attitude and criticism of people towards these technologies (Figure 5).

The mathematical formulation of this study is based on two main pillars: a deterministic economic optimisation of a European SC for CCS (d'Amore and Bezzo, 2017), and a quantitative technique for measuring public acceptance through risk perception at countrywide level (Karimi and Toikka, 2018). We recognise that there are a number of assumptions and simplifications, which are discussed in the following:

- the installation of transport/sequestration infrastructure in a country will likely create a debate, which may modify the perception on CCS and affect how future enlargements or installation may be perceived; in our model we assume that the entire European CCS SC is simultaneously built, thus neglecting possible positive or negative feedback effects on perception depending on the time evolution of the CCS infrastructure;

- it is assumed that risk is proportional to the size of the transportation pipeline and/or sequestration basin; although this seems a sensible approach, there is no information available assessing whether risk perceptions indeed increases linearly with size or an alternative correlation would be more realistic;
- it is well known that political propaganda, mass media, information campaigns may change people perception even in a relatively short-term; this introduces a level of uncertainty, whose effects cannot be neither quantified, nor forecasted, and therefore they are not taken into account in the proposed framework;
- also in view of the above, survey data should be periodically updated; we have referred to the most recent data available at a European level (Eurobarometer, 2011), but the situation is continuously changing and evolving;
- as in previous studies (d'Amore and Bezzo, 2017), coal- and gas-fired power plants are considered as the only sources of CO_2, neglecting the contribution of industrial facilities to overall emissions. Although this is a simplification, it is nonetheless a fact that these power plants are the only points of very high emission of CO_2 (>10^6 t of CO_2/year) and they generate about 37% of the overall yearly stationary CO_2 emissions in Europe (IPCC, 2018).
- the potential of combined carbon utilisation and sequestration (CCUS) is not taken into account; although its impact in terms GHG emission is still debated (Mac Dowell et al., 2017; Alper and Orhan, 2017), a recent study (Arning et al., 2019) suggests that carbon utilisation has a more favourable response in terms of public acceptance; it may therefore be used synergistically to maximise acceptance.

Notwithstanding such limitations, we believe that this work represents a significant step forward to assess the design of CCS infrastructures. A model of public perception was incorporated within an optimisation framework to provide a quantitative tool to assess how social acceptance may affect the effective planning and deployment of a CCS infrastructure, and the costs incurred to address and minimise that risk. Furthermore, a positive feedback comes from the fact that in several cases, higher specific risk perception values are assigned to those countries where legislation was enforced to limit or even ban CO_2 storage on their territory, e.g. Germany and Poland; accordingly, results (Scenario C) show some correspondence between those countries where CCS deployment is avoided to reduce risk perception, and those in which CO_2 storage is indeed forbidden by actual regulations (European Commission, 2017). Although this cannot be deemed as a proper validation (additional political and social factors can contribute to this result), it nonetheless demonstrates that there is a good agreement between the model predictions and the actual national response to such issues.

5. Conclusions

This contribution proposed a mixed integer linear programming model for the design and optimisation of a European carbon capture, transport, and sequestration supply chain, including a quantitative assessment of countrywide community acceptance through measures of risk perception. Results show that the maximisation of social acceptance through the minimisation of risk perception (regardless of considerations on economic aspects) leads to offshore sequestration solutions with a (possibly unacceptable) a total costs of about 621 B€ (equal to 50.88 €/t of sequestered, i.e. +34% with respect to the economic optimum), due to a more complex supply chain configuration characterised by high transport (+434%) and sequestration (+853%) costs. A multi-objective optimisation analysis, however, allowed identifying a possible intermediate solution between the two conflicting objectives (i.e., economics against acceptance), capable of limiting risk perception, without excessively compromising the economic performance of the supply chain. Overall, the specific total cost of the supply chain increases to 41.25 €/t of sequestered CO_2 (+8% with respect to the best economic configuration), thus demonstrating that this configuration could represent a reasonable trade-off between the economic and community acceptance objectives.

The methodology may provide investors and policy makers with a quantitative tool to assess the possible response of local communities to the deployment of such technologies. The combination of this analysis with more inclusive strategies for a stronger engagement of local communities might constitute a key tool to foster an effective implementation of carbon capture and storage technologies. Furthermore, the proposed methodology is quite general and could be transferred to other geographical contexts in the world, on condition that data on socio-attitudinal characteristics of local population are available.

Future work should build up from this modelling framework and include more sophisticated social assessment models, possibly incorporating environmental criteria, too (e.g., the presence of natural parks or the impact on water reservoirs), and extending the analysis to other (e.g., industry-related) emission points. Moreover, CO_2 utilisation should be investigated and incorporated in the optimisation framework.

Bibliography

Acar, C., Beskese, A., Temur, G.T., 2019. A novel multicriteria sustainability investigation of energy storage systems. Int. J. Energy Res. 6419–6441. doi:10.1002/er.4459

Alper, E., Yuksel Orhan, O., 2017. CO_2 utilization: Developments in conversion processes. Petroleum 3, 109–126. doi:10.1016/j.petlm.2016.11.003

Arning, K., Offermann-van Heek, J., Linzenich, A., Kaetelhoen, A., Sternberg, A., Bardow, A., Ziefle, M., 2019. Same or different? Insights on public perception and acceptance of carbon capture and storage or utilization in Germany. Energy Policy 125, 235–249. doi:10.1016/j.enpol.2018.10.039

Ashworth, P., Bradbury, J., Wade, S., Ynke Feenstra, C.F.J., Greenberg, S., Hund, G., Mikunda, T., 2012. What's in store: Lessons from implementing CCS. Int. J. Greenh. Gas Control 9, 402–409. doi:10.1016/j.ijggc.2012.04.012

Ashworth, P., Wade, S., Reiner, D., Liang, X., 2015. Developments in public communications on CCS. Int. J. Greenh. Gas Control 40, 449–458. doi:10.1016/j.ijggc.2015.06.002

Ashworth, P., Sun, Y., Ferguson, M., Witt, K., She, S., 2019. Comparing how the public perceive CCS across Australia and China. Int. J. Greenh. Gas Control 86, 125–133. doi:10.1016/j.ijggc.2019.04.008

Beamon, B., 1998. Supply chain design and analysis: models and methods. Int. J. Prod. Econ. 281–294.

Braun, C., 2017. Not in My Backyard: CCS Sites and Public Perception of CCS. Risk Anal. 37, 2264–2275. doi:10.1111/risa.12793

Bui, M., Adjiman, C.S., Bardow, A., Anthony, E.J., Boston, A., Brown, S., Fennell, P.S., Fuss, S., Galindo, A., Hackett, L.A., Hallett, J.P., Herzog, H.J., Jackson, G., Kemper, J., Krevor, S., Maitland, G.C., Matuszewski, M., Metcalfe, I.S., Petit, C., Puxty, G., Reimer, J., Reiner, D.M., Rubin, E.S., Scott, S.A., Shah, N., Smit, B., Trusler, J.P.M., Webley, P., Wilcox, J., Mac Dowell, N., 2018. Carbon capture and storage (CCS): The way forward. Energy Environ. Sci. 11, 1062–1176. doi:10.1039/c7ee02342a

Ervural, B.C., Evren, R., Delen, D., 2018. A multi-objective decision-making approach for sustainable energy investment planning. Renew. Energy 126, 387–402. doi:10.1016/j.renene.2018.03.051

Cuéllar-Franca, R.M., Azapagic, A., 2015. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. J. CO2 Util. 9, 82–102. doi:10.1016/j.jcou.2014.12.001

d'Amore, F., Bezzo, F., 2017. Economic optimisation of European supply chains for CO_2 capture, transport and sequestration. Int. J. Greenh. Gas Control 65. doi:10.1016/j.ijggc.2017.08.015

d'Amore, F., Mocellin, P., Vianello, C., Maschio, G., Bezzo, F., 2018. Economic optimisation of European supply chains for CO_2 capture, transport and sequestration, including societal risk analysis and risk mitigation measures. Appl. Energy 223, 401–415. doi:10.1016/j.apenergy.2018.04.043

d'Amore, F., Sunny, N., Iruretagoyena, D., Bezzo, F., Shah, N., 2019. European supply chains for carbon capture, transport and sequestration, with uncertainties in geological storage capacity: Insights from economic optimisation. Comput. Chem. Eng. 129, 106521. doi:10.1016/j.compchemeng.2019.106521

Dütschke, E., 2011. What drives local public acceptance - Comparing two cases from Germany. Energy Procedia 4, 6234–6240. doi:10.1016/j.egypro.2011.02.636

EU GeoCapacity Project, 2009. Assessing European Capacity for Geological Storage of Carbon Dioxide [WWW Document]. URL www.geology.cz/geocapacity/publications

Eurobarometer, 2011. Public awareness and acceptance of CO_2 capture and storage. Bruxelles, Belgium.

European Commission, 2019. The European CCS Demonstration Project Network [WWW Document]. URL https://ccsnetwork.eu/

European Commission, 2017. Report from the commission to the European Parliament and the Council on Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide [WWW Document]. URL https://ec.europa.eu/commission/sites/beta-political/files/report-carbon-capture-storage_en.pdf

Global CCS Institute, 2017. Database of Current CCS Projects [WWW Document]. URL https://www.globalccsinstitute.com/status

Groothuis, P.A., Groothuis, J.D., Whitehead, J.C., 2008. Green vs. green: Measuring the compensation required to site electrical generation windmills in a viewshed. Energy Policy 36, 1545–1550. doi:10.1016/j.enpol.2008.01.018

Han, J.H., Lee, I.B., 2012. Multiperiod stochastic optimization model for carbon capture and storage infrastructure under uncertainty in CO_2 emissions, product prices, and operating costs. Ind. Eng. Chem. Res. 51, 11445–11457. doi:10.1021/ie3004754

Hasan, M.M.F., First, E.L., Boukouvala, F., Floudas, C.A., 2015. A multi-scale framework for CO_2 capture, utilization, and sequestration: CCUS and CCU. Comput. Chem. Eng. 81, 2–21. doi:10.1016/j.compchemeng.2015.04.034

Heuberger, C.F., Staffell, I., Shah, N., Mac Dowell, N., 2018. Impact of myopic decision-making and disruptive events in power systems planning. Nat. Energy 3, 634–640. doi:10.1038/s41560-018-0159-3

Hofstede, G., Hofstede, G.J., Minkov, M., 2010. Cultures and Organizations, Software of the Mind, Intercultural Cooperation and Its Importance for Survival, 3rd Ed. ed. MacGraw-Hill, New York, U.S.A.

Huijts, N.M.A., Midden, C.J.H., Meijnders, A.L., 2007. Social acceptance of carbon dioxide storage. Energy Policy 35, 2780–2789. doi:10.1016/j.enpol.2006.12.007

IEA, 2015. Energy technology perspective 2015. Mobilising Innovation to Accelerate Climate Action. Paris, France.

IPCC, 2005. IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [WWW Document]. Cambridge Univ. Press. URL https://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf

IPCC, 2018. Global warming of 1.5 °C. An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate chang [WWW Document]. URL http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf

JRC, 2016. Emission Database for Global Atmospheric Research (EDGAR) [WWW Document]. URL edgar.jrc.ec.europa.eu/index.php

Karimi, F., Toikka, A., 2018. General public reactions to carbon capture and storage: Does culture matter? Int. J. Greenh. Gas Control 70, 193–201. doi:10.1016/j.ijggc.2018.01.012

Karimi, F., Toikka, A., Hukkinen, J.I., 2016. Comparative socio-cultural analysis of risk perception of Carbon Capture and Storage in the European Union. Energy Res. Soc. Sci. 21, 114–122. doi:10.1016/j.erss.2016.06.024

Kwak, D.-H., Kim, J.-K., 2017. Techno-economic evaluation of CO_2 enhanced oil recovery (EOR) with the optimization of CO_2 supply. Int. J. Greenh. Gas Control 58, 169–184. doi:10.1016/j.ijggc.2017.01.002

L'Orange Seigo, S., Dohle, S., Siegrist, M., 2014. Public perception of carbon capture and storage (CCS): A review. Renew. Sustain. Energy Rev. 38, 848–863. doi:10.1016/j.rser.2014.07.017

Laumanns, M., Thiele, L., Zitzler, E., 2006. An efficient, adaptive parameter variation scheme for metaheuristics based on the epsilon-constraint method. Eur. J. Oper. Res. 169, 932–942. doi:10.1016/j.ejor.2004.08.029

Lee, S.Y., Lee, I.B., Han, J., 2019. Design under uncertainty of carbon capture, utilization and storage infrastructure considering profit, environmental impact, and risk preference. Appl. Energy 34–44. doi:https://doi.org/10.1016/j.apenergy.2019.01.058

Li, H., Jiang, H.D., Yang, B., Liao, H., 2019a. An analysis of research hotspots and modeling techniques on carbon capture and storage. Sci. Total Environ. 687, 687–701. doi:10.1016/j.scitotenv.2019.06.013

Li, C., Negnevitsky, M., Wang, X., Yue, W.L., Zou, X., 2019b. Multi-criteria analysis of policies for implementing clean energy vehicles in China. Energy Policy 129, 826–840. doi:10.1016/j.enpol.2019.03.002

Mac Dowell, N., Fennell, P.S., Shah, N., Maitland, G.C., 2017. The role of CO_2 capture and utilization in mitigating climate change. Nat. Clim. Chang. 7, 243–249. doi:10.1038/nclimate3231

Mula, J., Peidro, D., Díaz-Madroñero, M., Vicens, E., 2010. Mathematical programming models for supply chain production and transport planning. Eur. J. Oper. Res. 204, 377–390. doi:10.1016/j.ejor.2009.09.008

Nie, Z., Korre, A., Elahi, N., Durucan, S., 2017. Real Options Analysis of CO_2 Transport and Storage in the UK Continental Shelf under Geological and Market Uncertainties and the Viability of Subsidies for Market Development. Energy Procedia 114, 6612–6622. doi:10.1016/j.egypro.2017.03.1815

Oltra, C., Upham, P., Riesch, H., Boso, À., Brunsting, S., Dütschke, E., Lis, A., 2012. Public Responses to CO_2 Storage Sites: Lessons from Five European Cases. Energy Environ. 23, 227–248. doi:10.1260/0958-305X.23.2-3.227

Pang, M., Zhang, L., Liang, S., Liu, G., Wang, C., Hao, Y., Wang, Y., Xu, M., 2017. Trade-off between carbon reduction benefits and ecological costs of biomass-based power plants with carbon capture and storage (CCS) in China. J. Clean. Prod. 144, 279–286. doi:10.1016/j.jclepro.2017.01.034

Pietzner, K., Schumann, D., Tvedt, S.D., Torvatn, H.Y., Næss, R., Reiner, D.M., Anghel, S., Cismaru, D., Constantin, C., Daamen, D.D.L., Dudu, A., Esken, A., Gemeni, V., Ivan, L., Koukouzas, N., Kristiansen, G., Markos, A., Ter Mors, E., Nihfidov, O.C., Papadimitriou, J., Samoila, I.R., Sava, C.S., Stephenson, M.H., Terwel, B.W., Tomescu, C.E., Ziogou, F., 2011. Public awareness and perceptions of carbon dioxide capture and storage (CCS): Insights from surveys administered to representative samples in six European countries. Energy Procedia 4, 6300–6306. doi:10.1016/j.egypro.2011.02.645

Reiner, D.M., 2016. Learning through a portfolio of carbon capture and storage demonstration projects. Nat. Energy 1, 1–7. doi:10.1038/nenergy.2015.11

Reiner, D.M., 2015. Where can I go to see one? Risk communications for an 'imaginary technology.' J. Risk Res. 18, 710–713. doi:10.1080/13669877.2015.1040657

Roddis, P., Carver, S., Dallimer, M., Norman, P., Ziv, G., 2018. The role of community acceptance in planning outcomes for onshore wind and solar farms: An energy justice analysis. Appl. Energy 226, 353–364. doi:10.1016/j.apenergy.2018.05.087

Rubin, E.S., Davison, J.E., Herzog, H.J., 2015. The cost of CO_2 capture and storage. Int. J. Greenh. Gas Control 40, 378–400. doi:10.1016/j.ijggc.2015.05.018

Santibanez-Gonzalez, E.D.R., 2018. A modelling approach that combines pricing policies with a carbon capture and storage supply chain network. J. Clean. Prod. 167, 1354–1369. doi:10.1016/j.jclepro.2017.03.181

Schumann, D., 2017. Public Perception of CO_2 Pipelines. Energy Procedia 114, 7356–7366. doi:10.1016/j.egypro.2017.03.1867

Shogenova, A., Piessens, K., Holloway, S., Bentham, M., Martinez, R., Flornes, K.M., Poulsen, N.E., Wojcicki, A., Sliaupa, S., Kucharic, L., Dudu, A., Persoglia, S., Hladik, V., Saftic, B., Kvassnes, A., Shogenov, K., Ivask, J., Suarez, I., Sava, C., Sorin, A., Chikkatur, A., 2014. Implementation of the EU CCS directive in Europe: Results and development in 2013. Energy Procedia 63, 6662–6670. doi:10.1016/j.egypro.2014.11.700

Small, M.J., Wong-Parodi, G., Kefford, B.M., Stringer, M., Schmeda-Lopez, D.R., Greig, C., Ballinger, B., Wilson, S., Smart, S., 2019. Generating linked technology-socioeconomic scenarios for emerging energy transitions. Appl. Energy 239, 1402–1423. doi:10.1016/j.apenergy.2019.01.215

Tapia, J.F.D., Lee, J.Y., Ooi, R.E.H., Foo, D.C.Y., Tan, R.R., 2018. A review of optimization and decision-making models for the planning of CO_2 capture, utilization and storage (CCUS) systems. Sustain. Prod. Consum. 13, 1–15. doi:10.1016/j.spc.2017.10.001

ter Mors, E., Terwel, B.W., Daamen, D.D.L., 2012. The potential of host community compensation in facility siting. Int. J. Greenh. Gas Control 11, 130–138. doi:10.1016/j.ijggc.2012.07.002

ter Mors, E., Terwel, B.W., Daamen, D.D.L., Reiner, D.M., Schumann, D., Anghel, S., Boulouta, I., Cismaru, D.M., Constantin, C., de Jager, C.C.H., Dudu, A., Esken, A., Falup, O.C., Firth, R.M., Gemeni, V., Hendriks, C., Ivan, L., Koukouzas, N., Markos, A., Næss, R., Pietzner, K., Samoila, I.R., Sava, C.S., Stephenson, M.H., Tomescu, C.E., Torvatn, H.Y., Tvedt, S.D., Vallentin, D., West, J.M., Ziogou, F., 2013. A comparison of techniques used to collect informed public opinions about CCS: Opinion quality after focus group discussions versus information-choice questionnaires. Int. J. Greenh. Gas Control 18, 256–263. doi:10.1016/j.ijggc.2013.07.015

Terwel, B.W., Harinck, F., Ellemers, N., Daamen, D.D.L., Best-Waldhober, M.D., 2009. Trust as predictor of public acceptance of CCS. Energy Procedia 1, 4613–4616. doi:10.1016/j.egypro.2009.02.282

Terwel, B.W., ter Mors, E., 2015. Host community compensation in a carbon dioxide capture and storage (CCS) context: Comparing the preferences of Dutch citizens and local government authorities. Environ. Sci. Policy 50, 15–23. doi:10.1016/j.envsci.2015.01.015

Turk, G.A., Cobb, T.B., Jankowski, D.J., Wolsky, A.M., Sparrow, F.T., 1987. CO_2 Transport: A new application of the assignment problem. Energy 12, 123–130. doi:https://doi.org/10.1016/0360-5442(87)90116-2

Upham, P., Oltra, C., Boso, À., 2015. Towards a cross-paradigmatic framework of the social acceptance of energy systems. Energy Res. Soc. Sci. 8, 100–112. doi:10.1016/j.erss.2015.05.003

van der Horst, D., Toke, D., 2010. Exploring the landscape of wind farm developments; local area characteristics and planning process outcomes in rural England. Land use policy 27, 214–221. doi:10.1016/j.landusepol.2009.05.006

Wallquist, L., Seigo, S.L.O., Visschers, V.H.M., Siegrist, M., 2012. Public acceptance of CCS system elements: A conjoint measurement. Int. J. Greenh. Gas Control 6, 77–83. doi:10.1016/j.ijggc.2011.11.008

Wang, J., Zhao, J., Wang, Y., Deng, S., Sun, T., Li, K., 2017. Application potential of solar-assisted post-combustion carbon capture and storage (CCS) in China: A life cycle approach. J. Clean. Prod. 154, 541–552. doi:10.1016/j.jclepro.2017.04.021

Wolsink, M., 2018. Social acceptance revisited: gaps, questionable trends, and an auspicious perspective. Energy Res. Soc. Sci. 46, 287–295. doi:10.1016/j.erss.2018.07.034

Yang, L., Zhang, X., McAlinden, K.J., 2016. The effect of trust on people's acceptance of CCS (carbon capture and storage) technologies: Evidence from a survey in the People's Republic of China. Energy 96, 69–79. doi:10.1016/j.energy.2015.12.044

Zhu, L., Duan, H.B., Fan, Y., 2015. CO_2 mitigation potential of CCS in China - An evaluation based on an integrated assessment model. J. Clean. Prod. 103, 934–947. doi:10.1016/j.jclepro.2014.08.079

Competing interests

The authors declare no competing interests.

Additional information

Supplementary material is available for this paper.

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Introducing social acceptance into the design of CCS supply chains: a case study at a European level

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Supplementary material

Table of contents

List of symbols

Acronyms

CCS	Carbon capture and storage
EU	European Union
GHG	Greenhouse Gas
IDV	Individualism vs. collectivism
IEA	International Energy Agency
IVR	Indulgence vs. restraint
LTO	Long-term orientation
MAS	Masculinity vs. femininity
MILP	Mixed integer linear programming
NIMBY	Not-in-my-back-yard
OptG	Optimality gap
PDI	Power distance index
SC	Supply chain
SolT	Solution time
UAI	Uncertainty avoidance index

Sets

c	Country, c={list of European countries}
d	Cultural dimension, d={PDI, UAI, LTO, IDV, MAS, IVR}
D	Set of possible pipeline inner diameters, $D=\{i, ii, iii\}$
g	Region, $g=\{1, 2, \ldots, 133, 134\}$
k	Capture technology, $k=\{post^{comb}_{coal}, post^{comb}_{gas}, oxy^{fuel}_{coal}, pre^{comb}_{gas}\}$
l	Transport mode, l={onshore, offshore}
p	Carbon flowrate, $p=\{1, 2, \ldots, 6, 7\}$

Parameters

α	European carbon reduction target [%]
$A_{p,g,g'}$	Sectional area of pipeline transporting p from g to g' [m^2]
C^{max}_g	Quantity of CO_2 generated in region g [t of CO_2]
δ^{CO_2}	Average density of the CO_2 [0.85 t/m^3]
$dim_{d,c}$	Hofstede's cultural dimension d in country c
$\Phi_{D,p}$	Pipeline inner diameter for set D for transporting flowrate p [m]
LD_g	Size of region g [km]
$LD_{g,g'}$	Linear distance between region g and g' [km]
N^{max}	Maximum flowrate processed by a single well [t of CO_2]
Pop_g	Population in region g
$\overline{Pop}_{g,g'}$	Average population between region g and g'
Q_p	CO_2 flowrate [1, 5, …, 25, 30 Mt of CO_2/year]
$risk_g$	Risk parameter in region g of country c [$(\text{people})^{-1}\cdot(\text{t of } CO_2)^{-1}$]

$\overline{risk}_{g,g'}$	Average risk parameter between region *g* and *g'* [(people)$^{-1}$·(t of CO_2)$^{-1}$]
S_g^{max}	Maximum storage availability in region *g* [t of CO_2]
τ_g	Terrain factor in region *g*
UCC_k	Unitary capture cost of technology *k* [€/t of CO_2]
USC_g	Unitary sequestration cost in region *g* [€/t of CO_2]
$\overline{UTC}_l$	Average unitary transport cost of mode *l* [€/t of CO_2/km]
$UTC_{p,l}$	Unitary transport cost of flowrate *p* through mode *l* [€/t of CO_2/km]
W_d^{risk}	Weight of cultural dimension *d* for risk calculation

Variables

$C_{k,g}$	Captured flowrate through technology *k* in region *g* [t of CO_2]
$H_{g,g'}$	Pipeline holdup between region *g* and *g'* [t of CO_2]
N_g	Number of injection wells operating in region *g*
$Q_{p,g,l,g'}$	Flowrate *p* of CO_2 transported from *g* through *l* to *g'* [t of CO_2]
RP	Risk perception
RP^{seq}	Risk perception on sequestration stage
RP^{trans}	Risk perception on transport stage
S_g	Stored CO_2 in region *g* [t of CO_2]
TC	Total cost [€]
TCC	Capture cost [€]
TSC	Sequestration cost [€]
TTC	Transport cost [€]
TTC^{inter}	Total inter-connection cost between region *g* and *g'* [€]
TTC^{intra}	Total intra-connection cost within region *g* [€]

Binary variables

$\lambda_{p,g,l,g'}$	1 if transport *p* is performed from *g* through mode *l* to *g'*, 0 otherwise

1. Mathematical formulation

A European CCS SC is represented through a multi-echelon, time-static, spatially-explicit, multi-objective, MILP model, aiming at the simultaneous minimisation of total costs (*TC* [€]) and risk perception (*RP*):

$$\begin{cases} objective = \min(TC, RP) \\ s.t. \\ capture\ problem \\ transport\ problem \\ sequestration\ problem \\ social\ acceptance\ problem \end{cases} \tag{S1}$$

The modelling framework includes the capture, transport, sequestration, and social acceptance problems (described subsequently). The value of *TC* of Eq.(S1) is given by the sum of the overall installation and operation costs deriving from the capture (*TCC* [€]), transport (*TTC* [€]), and sequestration (*TSC* [€]) stages, while *RP* of Eq.(S1) is obtained according to the contributions of both transport (RP^{trans}) and sequestration (RP^{seq}) infrastructures in terms of risk perception:

$$TC = TCC + TTC + TSC \tag{S2}$$

$$RP = RP^{trans} + RP^{seq} \tag{S3}$$

Details on *TCC*, *TTC*, and *TSC* of Eq.(S2) can be found in the *capture problem*, *transport problem*, and *sequestration problem*, respectively. The quantification of RP^{trans} and RP^{seq} of Eq.(S3) is detailed through the *social acceptance problem*.

1.1 The capture problem

The total European capture costs (*TCC* [€]) of Eq.(S2) is obtained by multiplying unitary capture costs (UCC_k [€/t of CO_2]) (d'Amore and Bezzo, 2017) for processing CO_2 through technology *k*, by the locally captured amount of CO_2 ($C_{k,g}$ [t of CO_2) through technology *k* in region *g*:

$$TCC = \sum_{k,g} C_{k,g} \cdot UCC_k \tag{S4}$$

The overall quantity of CO_2 that is generated in region g (i.e., C_g^{max} [t of CO_2]) is taken from JRC (Joint Research Centre and European Commission, 2016), and determines the upper bound for the locally captured amount $C_{k,g}$ of CO_2, whereas the lower bound is set for all Europe through the European minimum carbon reduction target α:

$$\sum_{k} C_{k,g} \leq C_g^{max} \qquad \forall g \tag{S5}$$

$$\sum_{k,g} C_{k,g} \geq \alpha \cdot \sum_{g} C_g^{max} \tag{S6}$$

Then, captured quantities $C_{k,g}$ must be either sequestered within the same region g, or transported towards sequestration basins in a different region g', according to the mass balances set through the transport problem model.

1.2 The transport problem

The transport cost TTC of Eq.(S2) is given by two contributions: the inter-connection cost TTC^{inter} [€] between region g and g', and the intra-connection cost TTC^{intra} [€] within each region g:

$$TTC = TTC^{inter} + TTC^{intra} \tag{S7}$$

On the one hand, the term TTC^{inter} of Eq.(S7) is calculated according to unitary transport costs ($UTC_{p,l}$ [€/t of CO_2/km]) for size p and mode l, that are evaluated on the basis of scale effects on overall flowrate and pipeline length between region g and g':

$$TTC^{inter} = \sum_{p,g,l,g'} \left(Q_{p,g,l,g'} \cdot UTC_{p,l} \cdot \tau_g \cdot LD_{g,g'} \right) \tag{S8}$$

where $Q_{p,g,l,g'}$ represents the CO_2 flowrate that is transported through mode l of size p between regions g and g' (ranging from 1 Mt of CO_2/year to 30 Mt of CO_2/year), τ_g is a tourtuosity factor for region g, and $LD_{g,g'}$ [km] is the linear distance between regions g and g'. The parameters $UTC_{p,l}$, τ_g, and $LD_{g,g'}$ are taken from the literature (d'Amore and Bezzo, 2017).

On the other hand, TTC^{intra} of Eq.(S7) accounts for costs of all short distance transport networks within region g (emerging when a capture infrastructure is active in region g) by taking into account an average value over possible sizes p of unitary transport cost $\overline{UTC_l}$ [€/t of CO_2/km], and the dimension LD_g [km] of cell g:

$$TTC^{intra} = \sum_{g,l} \left(C_{k,g} \cdot \overline{UTC_l} \cdot \frac{\sqrt{2}}{2} \cdot LD_g \right) \tag{S9}$$

The parameters $\overline{UTC_l}$ and LD_g are taken from previous work (d'Amore and Bezzo, 2017). Overall, the transport routes between regions g and g' (and possibly within region g) are set by aim of the CO_2 mass balance in region g:

$$\sum_k C_{k,g} + \sum_{p,l,g'} Q_{p,g',l,g} = \sum_{p,l,g'} Q_{p,g,l,g'} + S_g \qquad \forall g \tag{S10}$$

The term S_g [t of CO_2] of Eq.(S10) represents the amount of CO_2 stored in geological basins within region g.

1.3 The sequestration problem

The total sequestration cost TSC of Eq.(S2) is proportional to the number of injection wells N_g that need to be installed in region g:

$$TSC = \sum_g USC_g \cdot N_g \tag{S11}$$

where USC_g [€/well] is the unitary sequestration cost for installing and operating one injection well in region g (d'Amore and Bezzo, 2017). On the other hand, N_g of Eq.(S12) depends on the amount of CO_2 that is sequestered in region g according to S_g of Eq.(S10) and on the maximum flowrate N^{max} [t of CO_2] that can be processed through a single well (d'Amore and Bezzo, 2017):

$$S_g \cdot N^{max} = N_g \qquad \forall g \tag{S12}$$

The upper bound for the calculation of S_g of Eq.(S10) is given by the maximum storage availability S_g^{max} [t of CO_2] in region g, which was retrieved on the basis of the results provided by the literature (EU GeoCapacity Project, 2009):

$$S_g \leq S_g^{max} \qquad \forall g \tag{S13}$$

1.4 The social acceptance problem

Social acceptance is quantified in terms of risk perception RP through Eq.(S3), which is given by the combined contributions of both the risk emerging from the installation and operation both the transport (RP^{trans}) and sequestration (RP^{seq}) infrastructures. Overall, as will be detailed in the following, RP is calculated on the basis of the size of the CCS project, of the population inhabiting within the region, and of the differential behaviour of countries in terms of risk perception. RP^{trans} of Eq.(S3) is calculated considering the massive CO_2 holdup in the pipelines $H_{g,g'}$ [t of CO_2] as variable accounting for the scale of the transport, the average population $\overline{Pop}_{g,g'}$ [people] inhabiting between regions g and g', and the average parameter $\overline{risk}_{g,g'}$ [(people)$^{-1}$·(t of CO2)$^{-1}$] for risk perception calculation of regions g and g':

$$RP^{trans} = \sum_{g,g'} H_{g,g'} \cdot \overline{Pop}_{g,g'} \cdot \overline{risk}_{g,g'} \tag{S14}$$

In particular, $\overline{Pop}_{g,g'}$ of Eq.(S14) is taken from previous work (d'Amore et al., 2018) (Table S.1), $\overline{risk}_{g,g'}$ is calculated following the indications of the literature (Karimi and Toikka, 2018) (Table S.2), while $H_{g,g'}$ depends on the inner characteristics of the pipeline:

$$H_{g,g'} = \sum_{p,l} \left(\lambda_{p,g,l,g'} \cdot A_{p,g,g'} \cdot LD_{g,g'} \cdot \delta^{CO_2} \right) \qquad \forall g, g' \tag{S15}$$

where $\lambda_{p,g,l,g'}$ is a binary variable representing whether a pipeline l of size p is installed between regions g and g', $A_{p,g,g'}$ is calculated from the average values of inner diameters reported in Table S.3 (on which a subsequent sensitivity analysis will be performed) and represents the summation of pipelines sectional areas for transport capacities p between regions g and g', $LD_{g,g'}$ is the length of the pipeline installed between regions g and g', while δ^{CO_2} [0.85 t/m^3] is the average value of density of the CO_2 as taken from IPCC (IPCC, 2005), considering an average pressure of 15 MPa and temperature of 30°C. Furthermore, regarding risk perception on intra-connection systems within regions g, this formulation assumes that their contribution is indirectly accounted within that generated by the sequestration basins installed in region g. Indeed, if a sequestration basin is installed in region g therefore, at least one intra-connection mode is installed within the same region and its social acceptance is already quantified through the risk perception of the sequestration stage.

On the other hand, the risk perception RP^{seq} of Eq.(S3) generated by the installation and operation of injection facilities is calculated according to the population Pop_g [people] inhabiting in region g (Table S.1), to the size of the sequestration S_g in region g, and to the parameter $risk_g$ [(people)$^{-1}$·(t of CO2)$^{-1}$] for risk perception calculation in region g (Table S.2):

$$RP^{seq} = \sum_g S_g \cdot Pop_g \cdot risk_g \quad \text{(S16)}$$

Table S.1. Population Pop_g [people] in region g (d'Amore et al., 2018).

g		Pop_g	g		Pop_g	g		Pop_g	g		Pop_g
1	fin	623338	35	uk	17425077	69	mda	7149345	103	esp	2528046
2	fin	1444089	36	be	26442966	70	pt	2615241	104	esp	926370
3	fin	1138663	37	de	29740921	71	esp	2314727	105	ita	1187523
4	fin	1968386	38	de	22497971	72	esp	5967721	106	ita	6006687
5	fin	5344278	39	de	17420852	73	esp	9723700	107	ita	4151164
6	fin	4142946	40	de	18038080	74	fr	11996446	108	gr	3680987
7	fin	1225066	41	pl	17327507	75	ita	7854909	109	gr	5657679
8	dk	5554491	42	pl	22487959	76	ita	11991306	110	tur	7563776
9	fin	7322399	43	pl	23022237	77	ita	4360803	111	tur	13279758
10	fin	4406072	44	pl	24126788	78	ba	1845221	112	esp	5020666
11	fin	1990982	45	ukr	46977319	79	ba	12728932	113	alg	1793237
12	uk	6873434	46	ukr	33351472	80	srb	32031815	114	alg	1000000
13	uk	3619151	47	fr	20622020	81	ro	42373045	115	alg	1000000
14	dk	5373260	48	fr	9114312	82	ro	12593705	116	alg	1000000
15	dk	9818152	49	fr	12076934	83	ro	3373639	117	tun	1000000
16	ltu	6251886	50	de	20502070	84	pt	8411228	118	tun	429112
17	ltu	27114025	51	de	14078576	85	esp	4110680	119	ita	3066682
18	ltu	6060678	52	cz	9169064	86	esp	8623897	120	ita	1760777
19	irl	3739335	53	cz	13164287	87	esp	5861966	121	gr	579655
20	irl	4563479	54	svk	29700915	88	esp	11273828	122	gr	4646671
21	uk	15766328	55	svk	27000884	89	esp	6879932	123	gr	2491814
22	uk	23407982	56	ukr	11513991	90	ita	1145620	124	tur	4760194
23	nl	6650423	57	ukr	11980548	91	ita	4954248	125	uk	1
24	de	13801479	58	ukr	15537520	92	ita	21584173	126	uk	1
25	de	10960259	59	fr	9455965	93	ita	7104495	127	no	1
26	de	9867184	60	fr	12926570	94	alb	8554502	128	no	1
27	pl	5687484	61	ita	42298841	95	mkd	21993064	129	no	1
28	pl	10066478	62	ita	19151247	96	gr	17924647	130	uk	1
29	pl	12724572	63	ita	7475558	97	gr	7783208	131	no	1
30	pl	19531358	64	hrv	8101485	98	tur	17652641	132	dk	1
31	pl	35166724	65	hun	19896347	99	pt	5872477	133	uk	1
32	pl	21682044	66	ro	24303916	100	esp	7884497	134	nl	1
33	uk	8257058	67	ro	9508152	101	esp	12191710			
34	uk	25029302	68	ro	10898807	102	esp	8250115			

Table S.2. Parameter for the calculation of risk perception $risk_g$ [(people)$^{-1}$·(t of CO_2)$^{-1}$] in region g within country c (Karimi and Toikka, 2018). Because of the lack of data, for some countries approximations are used: for Ukraine (ukr) and Moldavia (mda) the value of Romania (ro) is used; for Bosnia (ba) and Albania (alb) the value of Serbia (srb) is used; for Macedonia (mkd) the value of Greece is used (gr); for Algeria (alg) and Tunisia (tun) the value of Morocco (mo) is used.

g		$risk_g$	g		$risk_g$	g		$risk_g$	g		$risk_g$
1	fin	94.8	35	uk	92.1	69	mda	112.8	103	esp	120.5
2	fin	94.8	36	be	153.6	70	pt	117.3	104	esp	120.5
3	fin	94.8	37	de	132.1	71	esp	120.5	105	ita	118.6
4	fin	94.8	38	de	132.1	72	esp	120.5	106	ita	118.6
5	fin	94.8	39	de	132.1	73	esp	120.5	107	ita	118.6
6	fin	94.8	40	de	132.1	74	fr	128.6	108	gr	148.2
7	fin	94.8	41	pl	115.1	75	ita	118.6	109	gr	148.2
8	dk	65.4	42	pl	115.1	76	ita	118.6	110	tur	120.4
9	fin	94.8	43	pl	115.1	77	ita	118.6	111	tur	120.4
10	fin	94.8	44	pl	115.1	78	ba	119.3	112	esp	120.5
11	fin	94.8	45	ukr	112.8	79	ba	119.3	113	alg	73
12	uk	92.1	46	ukr	112.8	80	srb	119.3	114	alg	73
13	uk	92.1	47	fr	128.6	81	ro	112.8	115	alg	73
14	dk	65.4	48	fr	128.6	82	ro	112.8	116	alg	73
15	dk	65.4	49	fr	128.6	83	ro	112.8	117	tun	73
16	ltu	111.7	50	de	132.1	84	pt	117.3	118	tun	73
17	ltu	111.7	51	de	132.1	85	esp	120.5	119	ita	118.6
18	ltu	111.7	52	cz	121.4	86	esp	120.5	120	ita	118.6
19	irl	75.3	53	cz	121.4	87	esp	120.5	121	gr	148.2
20	irl	75.3	54	svk	107	88	esp	120.5	122	gr	148.2
21	uk	92.1	55	svk	107	89	esp	120.5	123	gr	148.2
22	uk	92.1	56	ukr	112.8	90	ita	118.6	124	tur	120.4
23	nl	109	57	ukr	112.8	91	ita	118.6	125	uk	92.1
24	de	132.1	58	ukr	112.8	92	ita	118.6	126	uk	92.1
25	de	132.1	59	fr	128.6	93	ita	118.6	127	no	80
26	de	132.1	60	fr	128.6	94	alb	119.3	128	no	80
27	pl	132.1	61	ita	118.6	95	mkd	148.2	129	no	80
28	pl	115.1	62	ita	118.6	96	gr	148.2	130	uk	92.1
29	pl	115.1	63	ita	118.6	97	gr	148.2	131	no	80
30	pl	115.1	64	hrv	127.2	98	tur	120.4	132	dk	94.8
31	pl	115.1	65	hun	127.2	99	pt	117.3	133	uk	92.1
32	pl	115.1	66	ro	112.8	100	esp	120.5	134	nl	109
33	uk	92.1	67	ro	112.8	101	esp	120.5			
34	uk	92.1	68	ro	112.8	102	esp	120.5			

Table S.3. Inner pipeline diameter (Φ_p [m]) employed for the calculation of holdup areas $A_{p,g,g'}$ according to the pipelines capacity discretisation p (Knoope et al., 2013).

p	Q_p [Mt of CO_2/year]	Φ_p [m]
1	1	0.20
2	5	0.40
3	10	0.50
4	15	0.59
5	20	0.66
6	25	0.72
7	30	0.79

Regarding the parameter $risk_g$ reported in Table S.2, it is calculated according to the methodology proposed by Karimi and Toikka (Karimi and Toikka, 2018), where the public perception towards CCS characterised by risk perception $risk_c$ in each country c, constituted by regions g (as stated in the main text, benefit has been excluded from the modelling framework developed here). In particular, $risk_c$ can be evaluated for all regions g within country c according to the parameter $dim_{d,c}$, representing the values of Hofstede's cultural dimensions for set d={PDI, UAI, LTO, IDV, MAS, IVR} in country c (Hofstede et al., 2010) (Table S.4), and the parameter W_d^{risk}, representing the weights of cultural dimension d (Karimi and Toikka, 2018) (Table S.5).

Table S.4. Values of $dim_{d,c}$ of Hofstede's cultural dimensions *d* in country *c*.

	d					
C	PDI	UAI	LTO	IDV	MAS	IVR
Belgium	67	93	82	75	53	57
Croatia	73	80	58	33	40	33
Czech Republic	57	74	70	58	57	29
Denmark	18	23	35	74	16	70
Finland	33	59	38	63	26	57
France	68	86	63	71	43	48
Germany	35	65	83	67	66	40
Greece	60	112	45	35	57	50
Hungary	46	82	58	80	88	31
Ireland	28	35	24	70	68	65
Italy	50	75	61	76	70	30
Lithuania	42	65	82	60	19	16
Morocco	70	68	14	46	53	25
Netherlands	38	53	67	80	14	68
Norway	31	50	35	69	8	55
Poland	68	93	38	60	64	29
Portugal	63	104	28	27	31	33
Romania	90	90	52	30	42	20
Serbia	86	92	52	25	43	28
Slovakia	104	51	77	52	110	28
Spain	57	86	48	51	42	44
Turkey	66	85	46	37	45	49
United Kingdom	35	35	51	89	66	69

Table S.5. Weights W_d^{risk} of cultural dimensions *d* for the calculation of $risk_c$.

d	W_d^{risk}
PDI	-0.2
UAI	0.9
LTO	0.7
IDV	-0.1
MAS	0.2
IVR	0.4

2. Sensitivity analyses

2.1 Varying the European carbon reduction target

Figure A.1. CCS SC configuration under Scenario C, for different values of carbon reduction target α.

This section analyses the response of model to the variations of the European carbon reduction target α under Scenario C (i.e., the trade-off scenario between economic and social acceptance optimisations), from a minimum value of 20% to a maximum of 50%. Results in terms of SC configuration clearly show the evolution of the system when the lower bound for overall CO_2 capture is increased (Figure A.1). Offshore geological potential is the main storage option chosen to be exploited for low carbon reduction targets (in order to keep the level of risk perception as low as possible, without compromising too much the economic performance of the system) but, as long as

α increases, more and more CO_2 gets sequestered onshore, at the cost of generating some risk in terms of acceptance, while keeping infrastructural costs not too high. Overall, changing the European carbon reduction target confirms the results in terms of optimal configuration obtained for α=50% and described within the main text.

2.2 Varying the inner pipeline diameter

The methodology for the calculation of risk perception on transport stage is based on the holdup of a pipeline, which relies on the assumption of an averaged value of inner diameter of the pipeline for the different possible CO_2 flowrates p (Table S.3). Therefore, the model will be here tested on changes in the assumed pipeline inner diameter $\Phi_{D,p}$ [m] for transporting a CO_2 flowrate p (Table S.6), described through the set D={i, ii, iii} (Knoope et al., 2013).

Table S.6. Set of pipeline inner diameters $\Phi_{D,p}$ [m] of set D for transporting flowrate p.

		p						
D	$\Phi_{d,p}$	1	2	3	4	5	6	7
i	$\Phi_{i,p}$	0.13	0.29	0.38	0.45	0.50	0.55	0.60
ii	$\Phi_{ii,p}$	0.20	0.40	0.50	0.59	0.66	0.72	0.79
iii	$\Phi_{iii,p}$	0.28	0.49	0.62	0.72	0.82	0.90	0.98

Table S.7. Scenario B. Total cost *TC* [B€ or €/t of sequestered CO_2],capture cost *TCC* [B€ or €/t of sequestered CO_2],transport cost *TTC* [B€ or €/t of sequestered CO_2], sequestration cost *TSC* [B€ or €/t of sequestered CO_2], risk perception *RP* and optimality gap *OptG* [%], depending on the selection through set *D* of possible diameters Φ.

	TC		*TCC*		*TTC*		*TSC*		*RP*	*OptG*
D	[B€]	[€/t]	[B€]	[€/t]	[B€]	[€/t]	[B€]	[€/t]		[%]
i	629.5	51.77	454.9	37.41	148.9	12.24	25.7	2.11	3.8	5.4
ii	620.7	50.88	453.8	37.20	140.9	11.55	25.9	2.13	6.3	6.6
iii	633.1	51.80	473.5	38.74	133.9	10.96	25.6	2.09	10.3	6.8

Since diameters affect directly only the value of RP^{trans} (not the economic-related constraints), this sensitivity analysis was performed only on Scenario B (i.e., *RP* minimisation) for a carbon reduction target α=50%. Results (Table S.7) show that despite the slight increase, the value of RP^{trans} (and of total *RP*) is still negligible (it ranges from a minimum of 3.8, to a maximum of 10.3), with just minor modifications to the resulting SC configuration, while costs are almost unchanged between the cases obtained for different values of Φ. In conclusion, the model is only slightly sensitive to the assigned value of inner diameter for the calculation of the pipeline holdup, and results were proven robust on the variations of these input parameters.

Bibliography

d'Amore, F., Bezzo, F., 2017. Economic optimisation of European supply chains for CO2 capture, transport and sequestration. Int. J. Greenh. Gas Control 65, 99–116. doi:10.1016/j.ijggc.2017.08.015

d'Amore, F., Mocellin, P., Vianello, C., Maschio, G., Bezzo, F., 2018. Economic optimisation of European supply chains for CO2 capture, transport and sequestration, including societal risk analysis and risk mitigation measures. Appl. Energy 223, 401–415. doi:10.1016/j.apenergy.2018.04.043

EU GeoCapacity Project, 2009. Assessing European Capacity for Geological Storage of Carbon Dioxide [WWW Document]. URL www.geology.cz/geocapacity/publications

Hofstede, G., Hofstede, G.J., Minkov, M., 2010. Cultures and Organizations, Software of the Mind, Intercultural Cooperation and Its Importance for Survival, 3rd Ed. ed. MacGraw-Hill, New York, U.S.A.

IPCC, 2005. IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [WWW Document]. Cambridge Univ. Press. URL https://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf

Joint Research Centre, European Commission, 2016. Emission Database for Global Atmospheric Research (EDGAR) [WWW Document]. URL edgar.jrc.ec.europa.eu/index.php

Karimi, F., Toikka, A., 2018. General public reactions to carbon capture and storage: Does culture matter? Int. J. Greenh. Gas Control 70, 193–201. doi:10.1016/j.ijggc.2018.01.012

Knoope, M.M.J., Ramírez, A., Faaij, A.P.C., 2013. A state-of-the-art review of techno-economic models predicting the costs of CO2 pipeline transport. Int. J. Greenh. Gas Control 16, 241–270. doi:10.1016/j.ijggc.2013.01.005

Competing interests

The authors declare no competing interests.

Additional information

Supplementary material is available for this paper.

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